

# Re-accelerating expansion of the universe revealed by supernovae Ia and *Planck* data.

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**The possibility that we are living in a fast expanding and underdense local bubble has made many to debate if dark energy is needed to explain the apparent over-dimming of distant supernovae Ia (SNe Ia). Recently the *Planck* team has reported a lower value of Hubble constant and a larger matter density than known previously. Here we show that the lower Hubble constant is inconsistent with SNe Ia data, and the local bubble density is too low, unless it is also a global property of the universe at the present cosmic time. We suggest a new scenario that the universe expands at initially a low, then slightly higher, and finally much higher rate at present, corresponding to increasing Hubble constant with cosmic time. Therefore these data provide evidence for re-accelerating expansion of the universe, deviating from accelerating expansion described by the concordant cosmological model, but still not requiring preferred observers.**

Explorations of Type Ia supernovae (SNe Ia) have proven to be an extremely fruitful enterprise. For example, comparisons between the apparent magnitudes of the low and high redshift SNe Ia have allowed the discovery of the accelerating expansion of the universe (1, 2). The Hubble constant  $H_0$  is the single most important cosmological parameter, because it measures the expansion rate of the universe, provides the basic information on the age of the universe, and is a key parameter in determining other cosmological parameters. The best measurement of  $H_0$  can be made using nearby Type Ia supernovae (SNe Ia), which are currently the best standard candles in cosmology. Recently a 3.3% error of  $H_0$  is reported by calibrating these standard candles with many Cepheid variables in their host galaxies (3), which are the best distance indicators of the local universe. With such a small error and being independent of or at least insensitive to cosmological models,  $H_0$  can be used directly as a pre-determined parameter in determining other cosmological parameters (4). Being excellent standard candles, SNe Ia can also be used to

calibrate other candles to extend the distance ladder to much higher redshift, such as gamma-ray bursts (5) and super-Eddington accretion black holes (6).

However, the best measurement of  $H_0$  was made using eight nearby SNe Ia with redshift  $z$  from 0.0043 to 0.0072, yielding only a local Hubble constant  $H_{0,0}$  (at  $z \sim 0$ ), which may not necessarily be the same as the Hubble constant at a much higher redshift,  $H_{0,z}$  (at  $z \gg 0$ ; note that it is not the same as the commonly used Hubble parameter  $H(z)$ ). Indeed, just before the discovery of the accelerating expansion of the universe (1, 2), evidence was found that  $H_{0,0} > H_{0,z}$  by about 6%, where the boundary is around  $D_L \sim 70 h^{-1} \text{Mpc}$  and  $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (7). This suggests that we are living within a small local Hubble bubble of radius about  $70 h^{-1} \text{Mpc}$ , which expands slightly faster than the outside universe. This means that we are moving away with respect to distant SNe Ia faster than the global Hubble expansion and thus the distant SNe Ia should look dimmer than viewing only within the Hubble flow. This thus has led many to debate if the ac-

celerating expansion of the universe is simply an mirage of this local Hubble bubble (8–16), since the over-dimming of distant SNe Ia is what led to the initial discovery of the accelerating expansion of the universe, which has been explained as due to the yet unknown dark energy (1, 2).

Similar to the previous work (7), in Figure 1 we show  $H_0$  measured from the currently best available SNe Ia data, i.e. the eight SNe Ia used to obtain  $H_{0,0}$  and the Union 2.1 compilation (17) used here to measure  $H_{0,z}$ . The data for the eight SNe Ia are listed in Table 1;  $h_0$  (with standard error  $\sigma_{h_0}$ ) is calculated using Equation (4) and data in Table 3 of Ref. (3).  $h_0$  for other SNe Ia is calculated using the standard method, e.g., Equation (12) or (13) in Ref. (18) with the same choices of parameters. We limit the SNe Ia with  $z < 0.04$  (with a median redshift of  $z_1 = 0.025$ ), in order to avoid any coupling with cosmological parameters; in fact it is already safe to choose  $z < 0.1$  (18). We obtain  $h_{0,0} = 0.738 \pm 0.0155$  and  $h_{0,z_1} = 0.704 \pm 0.0051$ , and  $H_{0,0} > H_{0,z_1}$  at 96.4% confidence level (see the figure caption for details). Following the Hubble’s law  $V_r = H_0 R$ , in which  $V_r$  is the receding velocity of a distant galaxy and  $R$  is its radial distance from the observer, the above result indicates that our local universe is expanding at a greater rate than the distant universe. This confirm the previous result (7) with the most updated and best available data.

A striking new result just released by the Planck team is that  $\Omega_M = 0.307 \pm 0.019$  and  $h_{0,z_2} = 0.679 \pm 0.015$  and ( $z_2 \approx 1100$ ) (19), the latter of which is even lower than  $h_{0,z_1}$ , as also shown in Figure 1. This result is actually consistent with some earlier reports (20, 21). In Figure 2, we examine the consistency of the three different Hubble constant, i.e.,  $h_{0,0}$ ,  $h_{0,z_1}$  and  $h_{0,z_2}$  against the Union 2.1 SNe Ia data at both low and high redshift, within the framework of the  $\Lambda$ CDM model with different values of  $\Omega_M$ . As expected, only  $h_0 = 0.704$  is consistent with data at low redshift ( $z_1 = 0.025$ ), independent of  $\Omega_M$ . At high redshift ( $z_2 = 0.740$ ), again only  $h_0 = 0.704$  is consistent with data unless  $\Omega_M$  deviates significantly from the well-measured and widely accepted value of around 0.3; actually the high redshift SNe Ia data favors a slightly lower  $\Omega_M$ , consistent with the definition of  $\Omega_M \equiv 8\pi G\rho_0/H_0^2$  for a constant  $\rho_{H_0}$ . It is thus very unlikely that SNe Ia data can be reconciled with either the higher or lower  $h_0$  measured in the local bubble or with the cosmic microwave background data with *Planck*, respectively.

From each listed  $H_{0,0}$  (measured in the local bubble) and its error in Table 1, the pure statistical error of  $h_{0,0}$  should be 0.009, much smaller than the error of 0.0155 determined from the variance of the eight data points. This means that the probability that the data do not contain additional fluctuations is less than 0.68%. It has been known that the peculiar motions of the SNe Ia hosts may cause such fluctuations beyond the measurement statistical errors (22, 23). For a peculiar velocity ( $V_{\text{LOS}}$ ) along the line of sight (LOS), the deviation to its cosmological redshift ( $z$ ) is  $\Delta z = V(1+z)/c$ , where  $c$  is the speed of light. For  $V_{\text{LOS}} = 100 \text{ km s}^{-1}$  at  $z \ll 1$ ,  $\Delta z = 0.0003$ , comparable to redshift  $z = 0.0043$  to 0.0072 of the eight SNe Ia. Since  $H_0 \cong cz/D_L$  when  $z \cong 0$ , a non-negligible deviation to  $H_0$  may therefore be produced, if one takes the common practice of using its luminosity distance  $D_L$  to measure  $H_0$ .

The additional fluctuations caused by the random peculiar motions of the SNe Ia hosts can be found from  $\sigma_{h_{0,P}}^2 = \langle h_0^2 \rangle - \bar{\sigma}_{h_0}^2 = 0.0352^2$ , where  $\langle h_0^2 \rangle = \sum (h_{0,i} - \bar{h}_0)^2 / (n-1)$  and  $\bar{\sigma}_{h_0} = \sum \sigma_{h_{0,i}} / n = 0.0262$  ( $n = 8$ ); in fact  $\bar{\sigma}_{h_0} \simeq \sigma_{h_{0,P}}$ . Clearly  $\sigma_{h_{0,P}} > \bar{\sigma}_{h_0}$ , i.e., the average fluctuation to  $h_0$  caused by the putative random peculiar motions of SNe Ia hosts is larger than the measurement errors in  $h_0$ . This means that for the first time it is possible to measure the peculiar motion of each individual SNe Ia host with the extremely accurate measurement of  $h_{0,i}$  of each SNe Ia.

We then compare the measured  $|H_{0,i} - \bar{H}_0|$  with the expected deviations caused by different LOS peculiar velocities at low redshift in Figure 2; here  $\bar{H}_0 = H_{0,0}$ . The data are consistent with  $V_{\text{LOS}} \sim 100 \text{ km s}^{-1}$ . In Figure 3, we show the positions of the eight SNe Ia in equatorial coordinates and their LOS peculiar velocities from the Hubble flow (all these data are listed in Table 1); the detected peculiar motions do not show any significantly coordinated pattern (albeit with small number statistics) and thus are consistent with random motions with respect to the Hubble flow. For random peculiar motions,  $\langle V_{\text{Pec}}^2 \rangle$  (the variance of its space velocity  $V_{\text{Pec}}$ ) is related to  $\langle V_{\text{LOS}}^2 \rangle$  (the variance that of its LOS velocity  $V_{\text{LOS}}$ ) by  $\langle V_{\text{Pec}}^2 \rangle = \frac{n-1}{x} \langle V_{\text{LOS}}^2 \rangle$ , where  $n$  is the number of SNe Ia, and  $x$  follows a *gamma*-distribution,

$$p(x; \alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}, \quad (1)$$

where  $\Gamma(\alpha)$  is the commonly known  $\Gamma$ -function,  $\alpha$  and  $\beta$  are two parameters:  $\alpha = \frac{8}{35}(n-1)$  and  $\beta = \beta_0 +$

Table 1: Redshift, coordinates (J2000.0), Hubble constant and LOS peculiar velocities of the eight SNe Ia.

Name	redshift	Right ascension (hh:mm:ss)	Declination (dd:mm:ss)	Hubble Constant $H_0$ (km s <sup>-1</sup> Mpc <sup>-1</sup> )	LOS pec. vel. $V_{\text{LOS}}$ (km s <sup>-1</sup> )
1981b	0.0072	12:34:29.57	+02:11:59.3	70.37 (2.26)	-100.8 (66.7)
1990n	0.0043	12:42:56.68	+13:15:23.4	74.81 (2.75)	17.8 (48.3)
1994ae	0.0045	11:56:25.87	+55:07:43.2	76.38 (2.46)	47.3 (45.1)
1998aq	0.0055	10:47:01.94	+17:16:30.8	70.89 (2.61)	-65.2 (58.6)
1995al	0.0059	09:50:55.97	+33:33:09.4	76.87 (2.83)	74.1 (68.1)
2002fk	0.0070	03:22:05.71	-15:24:03.2	68.48 (2.83)	-151.9 (81.1)
2007af	0.0070	12:01:52.80	-18:58:21.7	81.43 (2.62)	218.2 (75.0)
2007sr	0.0063	14:22:21.03	-00:23:37.6	70.50 (2.59)	-84.8 (66.8)

$1/2\sqrt{2}(n-1)$ , where  $\beta_0 = 0.68269$ . For  $n = 8$  here, the 90% lower limit of  $x$  is  $x > 0.462$ . From the eight SNe Ia, we have  $\sqrt{\langle V_{\text{LOS}}^2 \rangle} = 91.2 \text{ km s}^{-1}$  (the measurement errors of  $V_{\text{LOS}}$  have been subtracted), which gives the expectation, most-likely and 90% upper limit values of  $\sqrt{\langle V_{\text{LOS}}^2 \rangle}$  as 163.4, 266.6 and 355.0  $\text{km s}^{-1}$ , respectively.

Peculiar motions of galaxies can also be measured indirectly with the two-point correlation function to quantify one of the redshift space distortions, i.e., the apparent elongation of the clustering of galaxies in redshift space along LOS, the so-called “fingers of God” effect caused by peculiar motions of galaxies. This was first tentatively observed with  $V_{\text{Pec}} \sim 200 - 600 \text{ km s}^{-1}$  for nearby galaxies (24) and later convincingly demonstrated with  $V_{\text{Pec}} \approx 400 \text{ km s}^{-1}$  in the 2dF redshift survey at a median redshift of  $z = 0.11$  (25). The 2dF result is consistent with  $\Omega_{\text{M}} \approx 0.3$ . Therefore the observed peculiar velocities of the eight SNe Ia suggest that the expectation, most-likely and 90% upper limit values of the local matter density  $\Omega_{\text{M,Loc}}$  are 0.04, 0.11 and 0.20, respectively, according to the Cosmic Virial Theorem (24), i.e.,  $\sqrt{\langle V_{\text{LOS}}^2 \rangle} \approx 800\Omega_{\text{M}}^{1/2} \text{ km s}^{-1}$ . Our local expanding bubble is thus most-likely underdense significantly, compared to the average matter density of the universe.

If the observed  $h_{0,0} = 0.738$  is caused by the underdense local bubble embedded in a Hubble expansion with  $h_0 = 0.704$ , then  $\Omega_{\text{M,Loc}}$  should be only about 10% lower than the global  $\Omega_{\text{M}}$ , and thus significantly larger than that measured above with the observed peculiar velocities of the eight SNe Ia. In other words, if the most recent universe expands at the same rate as the

early universe, our local Hubble constant should be even much larger than  $h_{0,0} = 0.738$ , due to the significant under-density in the local bubble. A way out is that the local bubble is actually the global property of the universe; observationally it becomes “local” because only a small volume of the most recent universe can be observed by any observer. In other words, an observer located anywhere in the universe at  $z \sim 0$ , with respect to the cosmic microwave background at  $z \sim 1100$ , should also observe the same local bubble. This is good news, since it naturally avoids the philosophical crisis if we are living in a specially chosen place in the universe, i.e., the center of the universe where the matter density is much lower.

Therefore the SNe Ia and *Planck* data support a new scenario that the universe expands initially at a low rate (at  $z \sim 1100$ ), then at a slightly higher rate (at  $z \lesssim 1$ ), and finally at a much higher rate at present (at  $z \sim 0$ ). We call this re-accelerating expansion of the universe, to distinguish it from the well-known accelerating expansion of the universe described by the  $\Lambda$ CDM model, dominated by dark energy and with a constant Hubble constant (1, 2). Mathematically this model of universe can be described with the well-known the Lemaître-Tolman-Bondi (LTB) model with  $\Lambda$ , in which the Hubble constant, and perhaps also other cosmological parameters, are functions of cosmic time only; however, it is not clear what drives the time varying Hubble constant and thus the re-accelerating expansion of the universe. Nevertheless, it has been shown that the Union 2.1 SNe Ia data also agree with the LTB model, but cannot distinguish between the LTB model and  $\Lambda$ CDM models alone (26). Finally we stress that this new sce-

nario can still maintain the Copernicus principle in the way that there is no preferred observer in the universe.

## References and Notes

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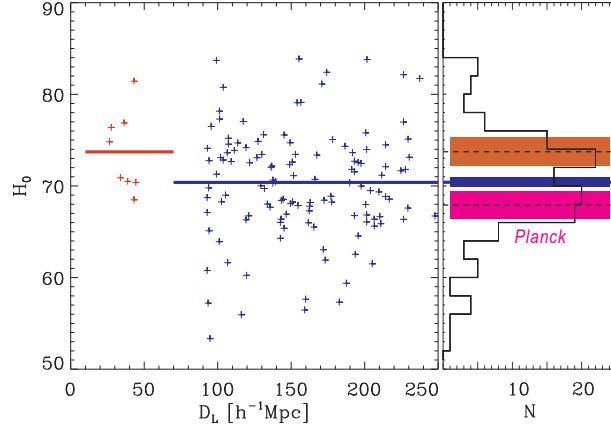


Figure 1: The Hubble constant  $h_0$  measured with each SNe Ia within a luminosity distance  $D_L$  of  $250 h^{-1}\text{Mpc}$ . **Left panel:** The red crosses are the eight best SNe Ia (3) used to measure the local  $H_0$  with  $D_L < 50 h^{-1}\text{Mpc}$ , giving an average local  $h_{0,0} = 0.738 \pm 0.0155$  marked as the thick solid red line. The blue crosses are the Union 2.1 SNe Ia (17) at  $D_L > 80 h^{-1}\text{Mpc}$ , yielding an average cosmological  $h_{0,z_1} = 0.704 \pm 0.0051$  as the thick solid blue line ( $z_1 = 0.025$  is the median redshift of these SNe Ia marked by the blue crosses). Seven of the eight SNe Ia (red crosses) have  $h_0 > h_{0,z_1}$ , indicating that the probability that the eight SNe Ia are drawn from the same population of the other SNe Ia (blue crosses) is less than 3.6%. **Right panel:** Histogram of the blue crosses in the left panel. The filled red and blue areas are the  $1\sigma$  error regions of  $h_{0,0}$  and  $h_{0,z_1}$  respectively; their errors are calculated from the variance of each sample, and are significantly larger than that calculated from error propagation using the measurement errors of all data points (see text for details). The large error in  $h_{0,0}$  is due to its very small sample size of only eight data points and additional fluctuations caused by the peculiar motions of their hosts (see text for details).  $h_{0,0}$  and  $h_{0,z_1}$  are different at  $2.1\sigma$  level with respect to their joint error bar, i.e., the probability that they are consistent with each other is less than 3.6%. For comparison, the just released *Planck* result  $h_{0,z_2} = 0.679 \pm 0.015$  is also marked by the filled magenta area ( $z_2 \sim 1100$ ).

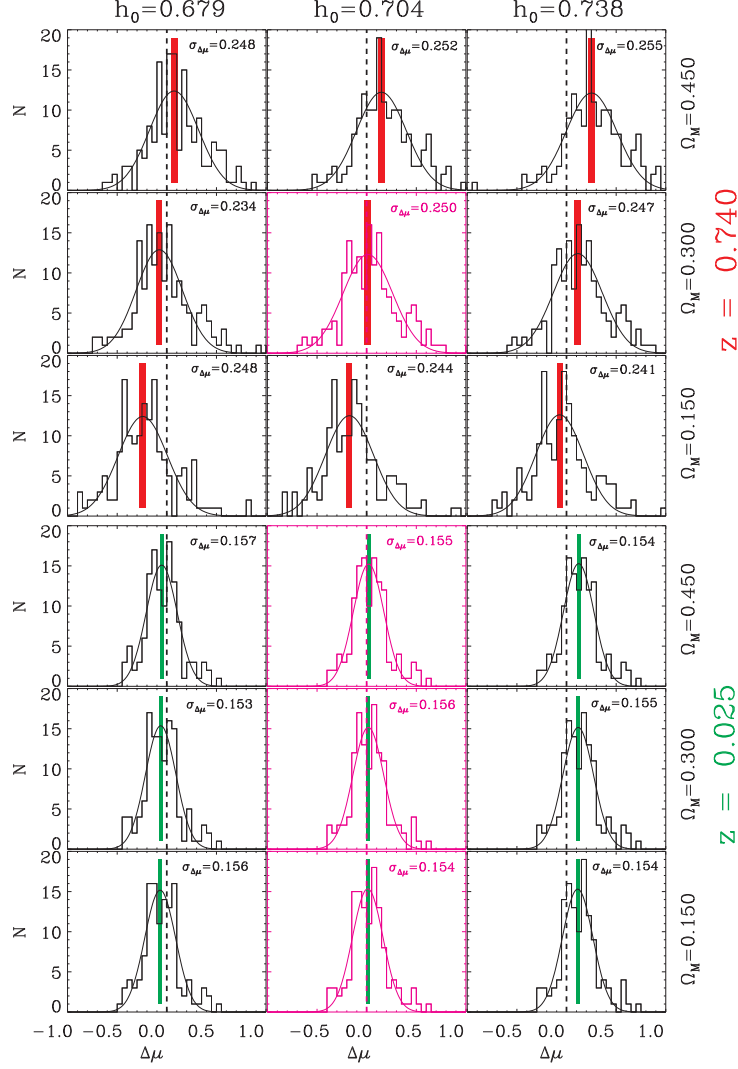


Figure 2: Residuals of the distance modules ( $\mu$ ) of the Union 2.1 SNe Ia against the prediction of the  $\Lambda$ CDM cosmological model with different combinations of  $\Omega_M$  and  $H_0$ ;  $\Omega_M + \Omega_\Lambda = 1$  is always assumed. The black thick vertical dashed lines indicate  $\Delta\mu = 0$ . Two groups of SNe Ia are chosen here: low redshift of  $z \leq 0.04$  with a median redshift of 0.025, and high redshift of  $z \geq 0.5$  with a median redshift of 0.740. The combination of the absolute value of  $\widehat{\Delta\mu}$  (the center of the distribution of  $\Delta\mu$ ) and the magnitude of  $\sigma_{\Delta\mu}$  (the standard deviation of each Gaussian fit, also labelled in each panel), indicates how well the model describes the data. Each filled area marks the  $3\sigma$  error range of  $\widehat{\Delta\mu}$  with  $\sigma_{\widehat{\Delta\mu}} = \sigma_{\Delta\mu}/\sqrt{n-1}$ , where  $n$  is the total number of data points. The four panels plotted in magenta color are consistent with data:  $h_0 = 0.704$  for  $z = 0.025$ , independent of  $\Omega_M$ ; also  $h_0 = 0.704$  for  $z_2 = 0.740$ , unless  $\Omega_M$  deviates significantly from 0.3.

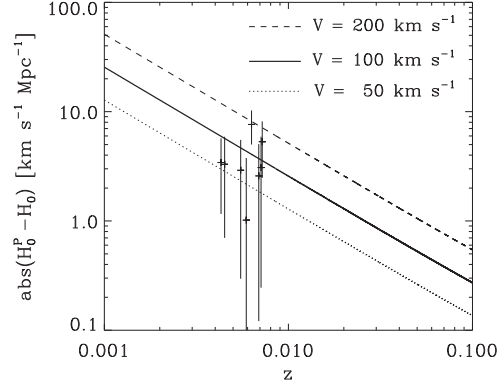


Figure 3: Deviations of the measured  $H_0$  with individual SNe Ia, caused by the peculiar motions of SNe Ia hosts at different redshift. The lines are the expected deviations for different peculiar velocities along the LOS. The data points with error bars are the deviations of the eight SNe Ia from  $h_{0,0} = 0.738$ . The data are consistent with the LOS peculiar velocity of about  $100 \text{ km s}^{-1}$ .

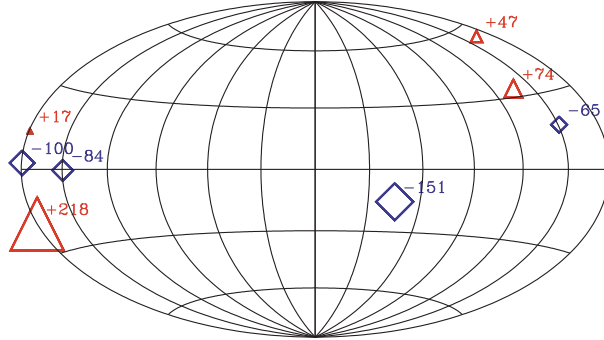


Figure 4: Positions of the eight SNe Ia in equatorial coordinates and their LOS peculiar velocities from the Hubble flow. Negative (marked as blue diamonds) and positive (marked as red triangles) velocities mean that their hosts are moving towards and away from the observer within the Hubble flow with  $h_{0,0} = 0.738$ , respectively. The sizes of the signs are proportional to their LOS velocity deviations.